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Top Decays in the Standard Model and Beyond

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1 Introduction

Top quark is by far the heaviest fermion in Standard Model (SM) and as such interesting when it comes to searches for physics beyond the SM. Precision studies of top quark properties are currently underway. In these proceedings we explore the possibility of new physics (NP) manifesting itself in rare top quark decays. In particular, we adopt an effective theory description of FCNC top quark decays and possible deviations from the SM form of tWb vertices.

FCNC top quark decays are being searched for at LHC and Tevatron. Due to the smallness of branching fractions predicted by SM, such decays are considered unobservable, meaning that potential experimental detection would indicate presence of NP. On the other hand, NP in charged quark currents impacting tWb vertices could be observed through the measurement of the helicity fractions of W bosons produced in the main decay channel of the top quark $t \rightarrow bW$.

Due to the outstanding role of the top quark in rare processes of meson physics, one should also consider the effects of NP in top quark sector on the well measured and theoretically understood processes in B and K physics.

2 NP in top quark FCNC decays

Within SM $t \rightarrow qV$ decays, where $q = u, c$ and $V = Z, \gamma, g$ are highly suppressed [1], with branching fractions of $\text{Br}[t \rightarrow cV] \sim 10^{-14} - 10^{-12}$, way below the reach of

experiments. Various models of NP can lift this suppression [2]. We parametrize NP manifestation in form of FCNC effective vertices as

$$\mathcal{L}_{\text{eff}} = \frac{v^2}{\Lambda^2} a_L^Z \mathcal{O}_L^Z + \frac{v}{\Lambda^2} \left[b_{LR}^Z \mathcal{O}_{LR}^Z + b_{LR}^\gamma \mathcal{O}_{LR}^\gamma + b_{LR}^g \mathcal{O}_{LR}^g \right] + (L \leftrightarrow R) + \text{h.c.} \quad (1)$$

For the definition of operators see Ref. [3]. Turning first to the indirect constraints of NP from meson physics, a detailed study has been performed in Ref. [5] and has shown that apart from \mathcal{O}_L operator, indirect constraints are not stringent enough to forbid the direct observation of FCNC decays at LHC¹.

Since there has, as of now, been no observation of FCNC top quark processes, upper 95% C.L. bounds on branching fractions have been obtained. In particular, ATLAS has set the following limit through single top production [7]

$$\text{Br}[t \rightarrow u, c\gamma] < 5.7 \times 10^{-5}, 2.7 \times 10^{-4}. \quad (2)$$

In addition, ATLAS [8] and CMS [9] report the following limits for the $t \rightarrow qZ$ decays

$$\text{Br}[t \rightarrow qZ] < 7.3 \times 10^{-3}, 2.4 \times 10^{-3}, \quad (3)$$

respectively. The bounds for photonic modes come from HERA [10] and CDF [11]

$$\text{Br}[t \rightarrow u\gamma] < 6.4 \times 10^{-3}, \quad \text{Br}[t \rightarrow q\gamma] = 3.2 \times 10^{-2}, \quad (4)$$

respectively. What is more, the study of projected sensitivities of ATLAS to Z and γ decay modes [12] predict probing branching fractions of the order $\text{Br}[t \rightarrow q\gamma, Z] \sim 10^{-5}$ with 100 fb^{-1} of collected data, promising substantial improvements of bounds in case no FCNC processes are observed.

In turn these bounds can be used together with theoretical predictions given in Refs. [3, 4] to constrain the effective couplings characterizing NP. Figure 1 summarizes the analysis for Z and γ channels. The obtained 95% C.L. bounds for all three channels read

$$\begin{array}{l|l} b^\gamma/\Lambda^2 < 0.86 \text{ TeV}^{-2}, & \text{for } q = u, \\ b^\gamma/\Lambda^2 < 1.93 \text{ TeV}^{-2}, & \text{for } q = u, c, \\ \hline a^Z/\Lambda^2 < 0.62 \text{ TeV}^{-2}, & \text{for } q = u, c, \\ b^Z/\Lambda^2 < 0.69 \text{ TeV}^{-2}, & \text{for } q = u, c, \end{array} \quad \left| \begin{array}{l} b^g/\Lambda < 6.9 \times 10^{-3} \text{ TeV}^{-1}, & \text{for } q = u, \\ b^g/\Lambda < 1.6 \times 10^{-2} \text{ TeV}^{-1}, & \text{for } q = c, \end{array} \right. \quad (5)$$

where the results for the gluonic anomalous couplings are derived in Ref. [7].

¹Matching between $SU(2)_L$ invariant operators used in Ref. [5] and those used in Eq. (1), can be found in Ref. [6]

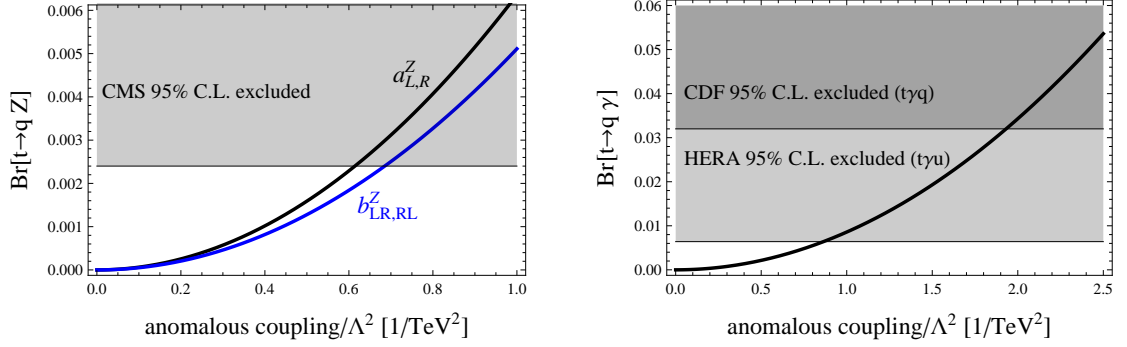


Figure 1: Graphs depicting the extraction of 95% C.L. bounds on anomalous top quark FCNC couplings through $t \rightarrow qZ$ (left) and $t \rightarrow q\gamma$ (right) decays.

3 NP in charged quark currents

Similarly to previous section, we can parametrize the effects of new physics in tWb vertex in term of anomalous couplings

$$\mathcal{L}_{\text{eff}} = a_L \mathcal{O}_L + b_{LR} \mathcal{O}_{LR} + (L \leftrightarrow R) + \text{h.c.}, \quad (6)$$

where \mathcal{O}_L and \mathcal{O}_{LR} operators are of vector and dipole type respectively and contain t , b and W fields².

Detailed analysis of indirect constraints from $\Delta B = 1, 2$ processes and electroweak precision observables has been performed in Refs. [14, 15, 16, 17]. The upshot is that Wilson coefficients accompanying operators \mathcal{O}_R and \mathcal{O}_{RL} and evaluated at the electroweak scale, are severely constrained $|a_R, b_{RL}| \lesssim 0.001$ (mostly through $b \rightarrow s\gamma$), while bounds for other Wilson coefficients are above percent level.

The structure of tWb vertex can be probed at LHC and Tevatron through the analysis of helicity fractions \mathcal{F}_i of W bosons produced in the main decay channel. Performing a naive average of Tevatron [18] and ATLAS [19] results we obtain the following experimental values to be compared with the state of the art SM predictions [20]

$$\begin{aligned} \mathcal{F}_L &= 0.692 \pm 0.053, & \mathcal{F}_+ &= -0.013 \pm 0.034, \\ \mathcal{F}_L^{\text{SM}} &= 0.687 \pm 0.005, & \mathcal{F}_+^{\text{SM}} &= 0.0017 \pm 0.0001. \end{aligned} \quad (7)$$

The small value of SM prediction for the chirally suppressed \mathcal{F}_+ makes this observable very appealing for NP searches, since a measured value of percent level would clearly indicate NP governing the decay.

²For exact definition see Ref. [13].

In Figure 2 we explore the effects of anomalous coupling b_{LR} on the helicity fraction. We only consider this coupling since a_R, b_{RL} are constrained from indirect considerations to such extent that we cannot expect them to notably impact the helicity fractions. On the other hand, a_L cancels out of the helicity fraction expressions as long as only one anomalous coupling is considered to be non-zero at a time. From

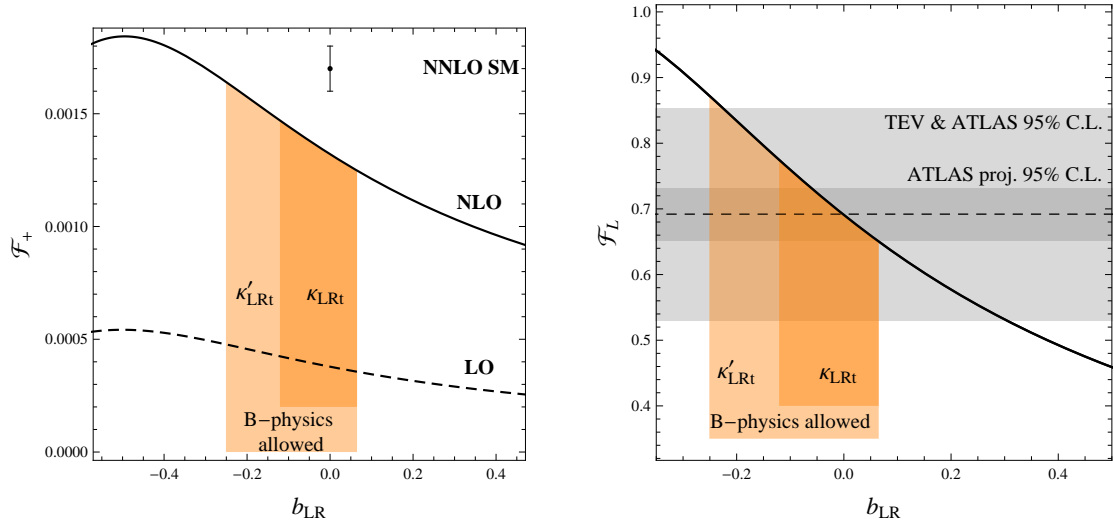


Figure 2: Dependence of \mathcal{F}_+ (left) and \mathcal{F}_L (right) on anomalous coupling b_{LR} which is considered to be real. Orange bands represent 95% C.L. intervals obtained from indirect considerations. On the right graph we show the combined experimental central value (dashed) and the 95% C.L. band along with the projected ATLAS band.

the graph on the lefthand side we can see that variation of the coupling b_{LR} can not, even at next-to-leading order in QCD, increase the helicity fraction to percent order or higher. Furthermore, from the righthand side graph we can infer that for the b_{LR} coupling the direct constraints from helicity fraction \mathcal{F}_L are competitive with the indirect and are further expected to constrain the coupling in the future.

4 Conclusions

In conclusion, rare top quark decays are interesting for NP considerations. Presence of NP in presented observables could easily be observed, however the SM compatible measurements are also beneficial since they serve to constrain various models of NP. Some of these direct constraints are for the first time becoming competitive with the indirect constraints from meson physics.

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